UTILITY APPLICATION

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TITLE: **FLEXIBLE ADD-DROP MULTIPLEXER FOR OPTICAL TELECOMMUNICATION NETWORKS**

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Documents Enclosed:

Specification (23 pgs); Claims (55 pgs); Abstract (1 pg); Drawings - Figures 1 - 6 (6 pgs); Declaration (2 pgs); Assignment & Recordation Coversheet (4 pgs); Grant of Power of Attorney (2 pgs); Utility Patent Application Transmittal (1 pg); Fee Transmittal (1 pg); Check for $2,384.00; Postcard.

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FLEXIBLE ADD-DROP MULTIPLEXER FOR OPTICAL TELECOMMUNICATION NETWORKS

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BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to optical transmission systems and, more particularly, to add-drop multiplexers used in optical wavelength division multiplexing networks.

2. Background

In optical transmission systems, data is converted into light impulses by modulating emitters at an ingress port, sent through a transmission medium, and received and demodulated at an egress port. The transmission medium is generally optical fiber, used because of its many advantages, including cost, low signal attenuation, high data throughput capacity, and relative insensitivity to electromagnetic interference.

"Optical" and "light" in this context are not limited to visible part of the electromagnetic spectrum, but cover part of the spectrum located between X-ray and microwave wavelengths. Broadly, optical part of the spectrum is considered to cover wavelengths between 10 nanometers and 1 millimeter. Two of the bands now commonly used in optical networks are 1310 nanometers and 1550 nanometers, both in the infrared region.

At the time of this writing, optical networks can transmit data on a single wavelength at speeds up to 10 Gbits per second (signal rate OC-192), and 40 Gbit/s (OC-768) systems are in the works. The theoretical limit of a single wavelength's bandwidth is much higher, and a fiber can typically support many discrete wavelengths.

Multiplication of telecommunication services and expanding bandwidth requirements of the services exert continuing pressure on existing telecommunications networks to increase their data carrying capacity. Techniques for increasing the data carrying capacity of fiber include frequency division multiplexing, and wavelength division multiplexing ("WDM"), often referred

to as dense wavelength division multiplexing ("DWDM") when a relatively high number of wavelengths are multiplexed.

Frequency division multiplexing increases the data carried by one wavelength. To date, this technology has not been widely commercialized.

DWDM multiplexes data onto multiple, independent optical data streams or channels on a single fiber. Each of the channels is carried by a different and distinct wavelength of light, typically emitted by a wavelength-specific laser modulated by a data signal. The number of channels per fiber can be as high as 128, and will likely continue to increase. DWDM technology is now widely used, especially in long-haul networks.

(In the preceding paragraph and throughout this document, *wavelength-specific* or *fixed-wavelength* means not dynamically reconfigurable in real time.)

One type of general architecture used in DWDM systems is *wavelength routing*. In a wavelength routed network, the path of each data stream through the network is determined by the stream's wavelength, the ingress port, and the setup of the network's routing elements, e.g., routers, switches, and wavelength converters.

A single wavelength may be associated with a data stream as it travels through the various nodes of the network. This is the *wavelength path routing* technique. The data stream may also be routed without a permanent association with a single wavelength. Instead, the wavelength carrying the data stream may be reassigned at optical cross connect ("OXC") nodes as the data stream travels from one span of the network to another. This is the *virtual wavelength path routing* technique.

A DWDM network, e.g., a SONET ring, will likely have more than two nodes. At some points along a fiber, additional nodes may need to add and/or remove ("drop" or divert) data stream(s) to and from the main signal path of the fiber. The added and dropped data streams may be locally generated. They may also come from other connections. (Network architecture may thus differ for various wavelengths; for example, it may be configured as a ring for wavelength λ_1, and provisioned as a point-to-point connection for λ_2.) Adding and dropping data streams is the function performed by add-drop multiplexers ("ADMs").

Optical add-drop multiplexer ("O-ADM") nodes are the optical network elements that integrate access and transport functions of optical networks. These devices add, drop, or pass-through selected wavelength channels in order to extend optical transparency over multiple fiber spans, a function that is gaining importance with increasing complexities of optical networks.

The emergence of wavelength routing network devices – optical cross connects and add-drop multiplexers – makes it in theory possible for "edge" client devices (i.e., network boundary access devices) to connect seamlessly to each other, thereby extending virtual network spans over great distances. To realize fully this theoretical possibility in practice, flexible optical access solutions are needed.

Presently available transparent O-ADM node designs do not yield full flexibility, since client-wavelength associations are fixed by physical port assignments. (By "transparent" I mean a single wavelength channel that is not transported as a payload of another layer data stream, such as SONET/SDH.) For example, suppose a data stream needs to be transported between nodes A and B. Suppose

further that the data stream is associated with wavelength λ_1 at node A because of the physical port assignment of the data stream on that node; in other words, the transmitter/modulator at node A of the port that receives the data stream is a wavelength-specific transmitter tuned to λ_1. If λ_1 is not available on the span between A and B (possibly because another channel is using λ_1), then the connection for the data stream will be denied or rerouted, even if another wavelength λ_2 is available between nodes A and B. The same problem arises if the receiver available at node B is not tuned to λ_1. This simple example illustrates the problem caused by fixed client-wavelengths associations.

Many O-ADM ring schemes are two- or four-fiber ring schemes, with different fibers carrying counter-propagating data flows. These schemes have evolved from electronic SONET/SDH ring schemes and are capable of replicating fast protection switching functionality in the optical domain. In contrast, most current O-ADM designs are based on opto-electronic (O-E) conversion. These schemes are not very scalable because they require high-speed electronic circuitry for each terminated and

originated wavelength channel. Furthermore, opto-electronic schemes usually rely on fixed data format/rate tributary signals (e.g., SONET/SDH, digital wrappers). Such solutions are therefore not transparent. As a result, most opto-electronic transport schemes require all client signals to be mapped into some payload format, and hence scale poorly and are not well suited to accommodating continually emerging newer, faster transmission formats.

Transparent optical O-ADM designs have also been proposed. Figure 1 illustrates an example of a basic two-fiber ring O-ADM node 100 for DWDM networks. (A similar configuration can also be drawn for four-fiber ring O-ADM design.) The data streams flow in opposite directions on the two fibers 105 and 110. The data stream of fiber 105 is received through fiber link Rx interface 115 and transmitted by fiber link Tx interface 120. Similarly, fiber link Rx and Tx interfaces 125 and 130 receive and transmit data streams of fiber 110, respectively. A bank of wide-band receivers 135 performs opto-electronic conversion of the received signals for possible routing of each signal to an electronic client through an associated

set of ITU-T interfaces 140. (*ITU-T* refers to standards propounded by the Telecommunications Standardization Sector of International Telecommunication Union, a standard-setting organization based in Geneva, Switzerland.) A second set of ITU-T interfaces 145 receives client signals and drives a bank of transponders 150. (The concept of *transponder* in this document is includes transmitters and modulators.) I mean either Each of the transponders can receive an optical data channel from an ITU-T interface and convert it to a different, fixed-wavelength channel for transmission over the network. The two fibers are coupled to wide band receivers 135 through sets of 2 x 1 switches 155 and 160, as shown; in the same fashion, transponders 150 are coupled to the fibers through sets of 2 x 1 switches 165 and 170. (The use of 2 x 1 switches in Figure 1 and other figures of this document is purely exemplary; other switch configurations may be used.)

Each set of switches has 2W 2 x 1 switches. As should be clear from Figure 1 to those of ordinary skill in the art, the "2W" quantity signifies two times the number of discrete wavelength channels on each of the

fibers. We assume here that each fiber has the same number W of such channels. More generally, if fiber 105 has W_1 channels and fiber 110 has W_2 channels, then the maximum number of required switches for both receive and transmit sides would be $2(W_1 + W_2)$.

With design configuration of Figure 1, the network operator must ensure that the ingress and egress optical ring nodes connect to the client devices at the correct pre-determined wavelength values. This "static" setup severely restricts the network wavelength routing algorithms, and therefore results in inherently increased ring channel blocking probabilities. As described above, even if a lightpath channel is available from an ingress optical ring node to an egress optical ring node, it may not be possible for the O-ADM device to use the channel because of discontinuity with the client port's wavelength association determined by the specific receiver and laser connected to the client. Many advanced higher-layer traffic engineering applications, such as those using multi-protocol label switching ("MPLS"), need the capability to open and/or close connections between multiple edge client routers dynamically. Hence, any O-

ADM setup that requires peer routers to be on the same wavelength channel will be restrictive, causing increased connection blocking and re-routing inefficiencies.

A limited, stop-gap solution here is to connect some of the ports on a client device (e.g., a router, an ATM switch, a SONET/SDH multiplexer) to multiple O-ADM ports, or even to all O-ADM ports. Although multiple port connections may improve the blocking probabilities, this solution has at least two major drawbacks. First, unless each client port is connected to each of the wavelengths, wavelength selection is still restricted. Second, client devices must purchase multiple connection ports, increasing bandwidth costs and reducing resource utilization for network service providers.

As the number of parallel fibers and the number of wavelength channels per fiber grow, the drawbacks of this multi-connection solution become more and more limiting.

Another approach is to use tunable transmitters and receivers. In other words, routing flexibility can be improved by replacing fixed-wavelength lasers in transponders 150 and filters in receivers 135 of Figure 1, with tunable variants of such components. These approach

requires very careful component calibration to prevent frequency drift, and presents much higher component and maintenance costs. Moreover, tunable lasers have not yet evolved sufficiently to gain broad acceptance and apparently are not widely available in the current marketplace.

What is needed, therefore, is O-ADM node design that scales well and allows dynamic selection of the wavelength at which a client signal is inserted into and extracted from the network.

SUMMARY OF THE INVENTION

The present invention is an optical system for switching physical channels, such as wavelength channels, in an optical communication network. The switching system may be an add-drop multiplexer, an add only multiplexer, or a drop only multiplexer. The switching system may provide a switching fabric interposed between channel inputs and a transponder block of the system, a switching fabric interposed between channel receivers and link receive side (e.g., an optical link receive interface or a bank of switches connected to an optical link receive

interface), or both switching fabrics. The optical switching system my further provide a bypass connection allowing some of the channels to bypass the multiplexer.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention will be described with particular embodiments thereof, and references will be made to the drawings in which:

FIG. 1, described above, illustrates an example of a basic two-fiber optical add-drop multiplexer node in a DWDM network.

FIG. 2 illustrates a flexible two-fiber add-drop multiplexer with transmit and receive optical switch fabrics.

FIG. 3 illustrates a single fiber optical add-drop multiplexer with transmit and receive optical switch fabrics.

FIG. 4 illustrates a two-fiber optical add-drop multiplexer with bypasses for selected channels on each of the fibers.

FIG. 5. illustrates an optical add-drop multiplexer with transmit and receive optical switch fabrics switching

to a reverse-direction (backup) path after a primary path fault.

FIG. 6 illustrates wavelength conversion in an intermediate node with an add-drop multiplexer having transmit and receive optical switch fabrics.

DETAILED DESCRIPTION

Figure 2 shows an add-drop multiplexer 200 in a two-fiber ring network. As in Figure 1, two data streams – two sets of wavelengths or channels – flow in opposite directions on a pair of fiber-optic cables 205 and 210. Fiber link Rx interfaces 215 and 225 receive their respective data streams and route them through sets of 2 x 1 switches 255 and 260, respectively, to a bank of wide-band receivers 235. Receivers 235 perform conversion of the received signals from an optical to an electronic format and route them to the clients through an associated set of interfaces 240. Interfaces 240 may, but need not, be ITU-T interfaces.

Unlike the multiplexer of Figure 1, the wide-band receivers are not directly coupled to the 2 x 1 switches of the fiber link Rx interfaces. Instead, receive optical switch fabric 275 is interposed between receive side switches 255/260

and wide-band receivers 235. In general, optical switch fabric 275 may be capable of switching each of the channels received from 2 x 1 switches 255/260 to any receiver of receiver bank 235. Optical switch fabric 275 may be more limited, with capability to switch fewer than all channels to fewer than all receivers.

Similarly, transmit optical switch fabric 280 is interposed between interfaces 245 and transponders 250, so that a signal input into each of the interfaces 245 can be routed to any of the fixed-wavelength transponders 250. Outputs of the transponders connect to fiber link Tx interfaces 220 and 230 through banks of switches 265 and 270. As in the case of the receive side, interfaces 245 may, but need not, be ITU-T interfaces; and the transmit optical switch fabric may have more limited switching capability.

A computer (not illustrated) controls the switches and the optical switch fabrics of add-drop multiplexer 200 to determine which of the channels are added, which are dropped, and which pass through the multiplexer. The computer may be a special purpose computer or a general purpose computer under control of routing software.

Note that the configuration of Figure 2 can be easily extended to a four-fiber ring O-ADM design. In fact the configuration will work with any number of fibers, including the rare case of a single-fiber network. A single-fiber O-ADM is illustrated in Figure 3. It is essentially one-half of the O-ADM of Figure 2.

The size of the matrices in receive and transmit optical switching fabrics of a ring network is generally much smaller than that required in larger, multi-fiber OXC-type devices. Specifically, because wavelength channels are often limited to those propagating along 2- or 4- fiber rings, the matrices are bounded by 2W x 2W and 4W x 4W sizes, respectively, with W denoting the number of wavelengths per fiber, as before.

In many applications, only a subset of wavelength channels may need to be sourced or sinked at a particular O-ADM node to achieve sufficient wavelength routing flexibility. In these applications there is no need for full-spectrum multiplexing or demultiplexing and ensuing per-wavelength processing described in connection with the O-ADM of Figure 2. To reduce hardware complexity and cost, some subset of N channels of the total number of channels can be selected for routing to all or a subset of receivers or transmitters of an O-ADM node. This

will reduce the size of the switching matrices. Moreover, either of the optical switching fabrics 275 and 280 (of Figure 2) may be eliminated, resulting in an O-ADM node capable of flexible routing on either the receive or the transmit side, but not both. This may be a cost effective solution where, for example, channel requirements are relatively constant in one direction.

Taking this matrix reduction approach in a slightly different direction, coarse (i.e., wide-band) filters may be used to add and/or drop selected sub-groups of wavelength channels. This second design is illustrated in Figure 4 for a two-fiber ring DWDM multiplexer. In this figure, all the elements familiar from Figure 2 appear in substantially the same relationship to each other, and perform substantially the same functions, including:

1. Optical fibers 405 and 410;

2. Fiber link Rx interfaces 415 and 425;

3. Sets of 2 x 1 switches 455 and 460 on the receive side;

4. A bank of wide-band receivers 435;

5. ITU-T receive interfaces 440;

6. Receive optical switch fabric 475;

7. Fiber link Tx interfaces 420 and 430;

8. Sets of 2 x 1 switches 465 and 470 on the transmit side;

9. Transponders 450;

10. Transmit optical switch fabric 480; and

11. ITU-T transmit interfaces 445.

In addition, the add-drop multiplexer of Figure 4 has optical signal splitter 482 at the input to fiber link Rx interface 415, optical signal combiner 484 at the output of fiber link transmit interface 420, optical signal splitter 486 at the input to fiber link Rx interface 425, optical signal combiner 488 at the output of fiber link transmit interface 430, and a pair of mux bypass connections 490 and 492. Mux bypass connection 490 between splitter 482 and combiner 484 transparently passes through the multiplexer a subset of N_1 wavelength channels (of the W_1 total wavelengths channels of fiber 405) with small signal losses. In the same fashion, mux bypass connection 492, splitter 486, and combiner 488 bypass a subset of N_2 wavelength channels of the W_2 channels of fiber 410.

As before, the number of the channels carried by each fiber need not be the same, and the number of fibers can vary.

One or more of the fibers may be bypassed, while other fiber or fibers may be connected as in Figure 2. The size of the subsets of bypassed channels can also vary from fiber to fiber.

The optical splitters and combiners appear as circulators in Figure 4. Circulators, based on Faraday effect, are non-reciprocal devices that direct light from port to port in one direction only. They are useful in combination with filters to minimize losses of the pass-through signals. But different devices can be used for bypassing, including, for example, simple power splitter/combiner pairs in combination with filters, comb filters, and interleavers.

The size of the switching fabric in the multiplexer of Figure 4 is thus decreased in comparison with the size of the multiplexer of Figure 2, because fewer channels need to be switched by the fabric. Moreover, fewer optical switches are needed because the bypassed channels do not require them, producing additional cost savings.

From the above discussion of the embodiments of the inventive O-ADMs, it should be clear that no specific type of switching fabric is required, as long as the switching fabric is capable of switching laser inputs from the client side and WDM laser inputs from the network side. For example, digital

electronic switching can be used, where the optical signals are first converted into electronic form, and then switched electronically. But at present time, optical spatial switching appears to be best suited to the task because of its high-bandwidth throughput and, as is implied by the "spatial" moniker, the ability to switch any input wavelength channel to any output. Considering the rapidly-declining cost of optical micro-electromechanical systems-based ("MEMS-based") switching fabrics and continuing improvements in their miniaturization and packaging, optical spatial switching may retain its advantages for some time.

Spatial switching improves optical lightpath blocking probabilities because it allows wavelength selection flexibility, and hence wavelength utilization, in both client signal insertion and extraction nodes. Client device (e.g., router) connectivity increases and, along with it, the effectiveness of higher-layer traffic engineering applications. The penalties associated with the use of spatial switching – cost and size – appear to be decreasing, especially considering the improvements being made in MEMS-based switching fabrics. Overall, for many network operators the resulting increased level of flexibility and resource utilization will more than

offset any additional costs potentially imposed by the use of switching fabrics in O-ADMs.

Fast protection switching is an important application of O-ADM rings. For example, in two fiber ring schemes, one fiber is typically used to carry data paths, while the other fiber is reserved for protection paths. A protection configuration for an embodiment of the invention is shown in Figure 5, where numeral 520 denotes a working (primary) lightpath channel from router 505 on outbound fiber 510. When transmission through fiber 510 is interrupted by primary channel fault 530, reverse-direction protection path for this channel can be chosen from any available transmitter/receiver pair of multiplexer 500 and the destination node's multiplexer, e.g., dashed lightpath 540. Here, the transmit side switching fabric must perform switchover to the available channel. The O-ADM with wavelength switching fabric, therefore, achieves a measure of wavelength conversion between working and protection paths.

When the backup fiber is not needed for protection paths, it can carry lower-priority, pre-emptible traffic. The added wavelengths flexibility between working and protection paths thus improves resource utilization and increases operator revenues.

Note that the invention can also provide wavelength conversion when the multiplexer node is an intermediate node. This is illustrated in Figure 6, where O-ADM 600 receives a data stream from node 610 on wavelength channel λ_1, routes it from receive side ITU-T interface 602 to transmit side ITU-T interface 604 over internal connection 606, and then routes it to node 620 over an available wavelength channel λ_2, which may differ from λ_1. Advantageously, the O-ADM that performs wavelength conversion also acts as a signal repeater because the signal is regenerated in the O-ADM for transmission on a different wavelength.

With regard to analog signal loss considerations, the 2 x 1 optical switches typically add approximately 0.5 dB each. Switch losses will, of course, be incurred in the more conventional O-ADM architecture shown in Figure 1, too. The optical switching fabric losses may be higher, e.g., 3-6 dB, depending upon the size of the fabric. But switching fabric loss is incurred two times, at most, upon signal insertion and extraction, and not per span.

Although I have discussed multiplexers that are capable of both adding and dropping channels, the principles of the invention are equally applicable to multiplexers that can only

add or drop channels, but not both. In such multiplexers, either some of the receive side components (receivers, optical switch fabric, receive side switches, receive side ITU-T interfaces), or some of the transmit side components (transponders, optical switch fabric, transmit side switches, transmit side ITU-T interfaces) need not be included.

It should be understood that the invention can find utility in applications other than DWDM systems with respect to which it has been described, and without regard to specific architectures addressed. Routing based on some physical characteristic of the signals is not limited to wavelength routing. Thus, the general principles can be extended *mutatis mutandis* to routing based on other physical characteristics, e.g., polarization or mode. And while certain aspects of the invention have been described in considerable detail with reference to specific embodiments thereof, other embodiments are possible. Some of the embodiments may not address all of the problems of existing multiplexers. Many modifications, changes, and variations are intended in the foregoing disclosure, and it will be appreciated by those of ordinary skill in the art that, in some instances, some features of the invention will be employed in the absence of a corresponding

use of other features, without departure from the scope of the invention as set forth. The illustrative examples therefore do not define the metes and bounds of the invention, which function has been reserved for the following claims and their equivalents.